Simulations of Wire Compensator in RHIC

H. J. Kim*, T. Sen, FNAL, Batavia, IL 60563, USA
N. P. Abreu and W. Fischer, BNL, Upton, NY 11973, USA

Beam-beam interaction is one of the dominant sources of emittance growth and luminosity lifetime deterioration. A current carrying wire has been proposed to compensate long-range beam-beam effects in the LHC and the principle is now being experimentally investigated at RHIC. Tune shift, beam transfer function, and beam loss rate are measured in dedicated experiments. In this paper, we do simulations to study the effect of wire compensator based on diffusive apertures, beam loss rates, and beam transfer function using a parallel weak-strong beam simulation code (bbsimc) without parasitic collisions. The simulation results are compared with measurements.

INTRODUCTION

Long-range beam-beam interactions are known to cause emittance growth or beam loss in the Tevatron and are expected to deteriorate beam quality in the LHC. A possible remedy to reduce their effects is to increase the crossing angle. However, it has a side effect which is to decrease the luminosity due to the geometric effect. Compensation of long-range beam-beam interactions by applying external electromagnetic forces has been proposed for the LHC. At large beam-beam separation, the electromagnetic force which a beam exerts on individual particles of the other beam is proportional to $\frac{1}{r}$, which can be generated and cancelled out by the magnetic field of a current-carrying wire. The test of this principle is now underway at RHIC. Two current carrying wires, one for each beam, have been installed at between the magnets $Q3$ and $Q4$ of IP6 in the RHIC tunnel. Their impact on a beam was measured during the physics run with deuteron and gold beams. No attempt was made to compensate the beam-beam interactions since there were no parasitic interactions in the experiments. However, the experiment results help understand the beam-beam effects because the wire force is similar to beam-beam one. In this report we discuss the results of numerical simulations of a wire acting on a beam in RHIC using a multi-particle tracking code together with measurement.

MODEL

A beam-beam simulation code `bbsimc` [1] has been developed at FNAL over the past few years. `bbsimc` can track multi-particles and simulate nonlinear effects in a high energy circular accelerator. The effects of the long-range interactions in a collider may be alleviated by using an appropriately placed current carrying wire with a well defined value of the current. In `bbsimc`, the integrated magnetic fields from the wire are applied as follows:

$$\begin{pmatrix} B_x \\ B_y \end{pmatrix} = \frac{\mu_0 I_w}{4\pi}\frac{u-v}{x^2+y^2}\begin{pmatrix} x \\ y \end{pmatrix}, \qquad (1)$$

where I_w is the current of wire compensator, u and v are $\sqrt{\left(\frac{3L_w}{2}\right)^2 + x^2 + y^2}$ and $\sqrt{\left(\frac{L_w}{2}\right)^2 + x^2 + y^2}$ respectively, and L_w the length of the wire. For cancelling the long-range beam-beam interactions with the wire, the integrated strength of the wire compensator should be commensurate with the integrated current of the beam bunch, i.e., $I_w L_w = ecN_b$, where N_b is the beam intensity. The parameters for RHIC long-range beam-beam compensators are listed in Table 1.

quantity	unit	value
gold energy	Gev/n	100
bunch intensity	10^9	1.0
emittance $\epsilon_{x,y}$(95%)	$mm\,mrad$	18
(β_x, β_y) at wire location	m	$(1299, 433)$
(σ_x, σ_y) at wire location	mm	$(6.0, 3.4)$
tunes (ν_x, ν_y)		B $(28.220, 29.231)$
		Y $(28.232, 29.228)$
$(IL)_{max}$	Am	125
L_w	m	2.5
r_w	mm	3.5
wire separation	σ_y	7-20

Table 1: RHIC parameters at gold-gold collision energy.

RESULTS

Figure 1 (top) presents average tune shift obtained by tracking multi-particles of which initial distribution is Gaussian. The tune shift from simulation is compared with the analytical result. The transverse tune shifts at zero amplitude due to wire kicks is given by

$$\Delta v_{x,y} = \pm\frac{\mu_0 I_w L_w}{8\pi^2 (B\rho)\,\sigma^2}\beta_{x,y}\frac{d_y^2 - d_x^2}{\left(d_y^2 + d_x^2\right)^2}, \qquad (2)$$

where $d_{x,y}$ denote the beam-wire distances normalized by rms beam size at wire location in horizontal and vertical directions respectively, $I_w L_w$ the integrated strength of the wire, and $\beta_{x,y}$ the beta functions at wire location. The changes in the transverse tune as a function of the beam-wire vertical separation distances is in good agreement with analytic relation, as shown in Fig. 1. The relative difference of vertical tune shift between simulation and theory is ~10% at $d_y = 7\sigma$, which stems from the finite amplitude of tracking particles. The measured tune shifts in the recent

* hjkim@fnal.gov

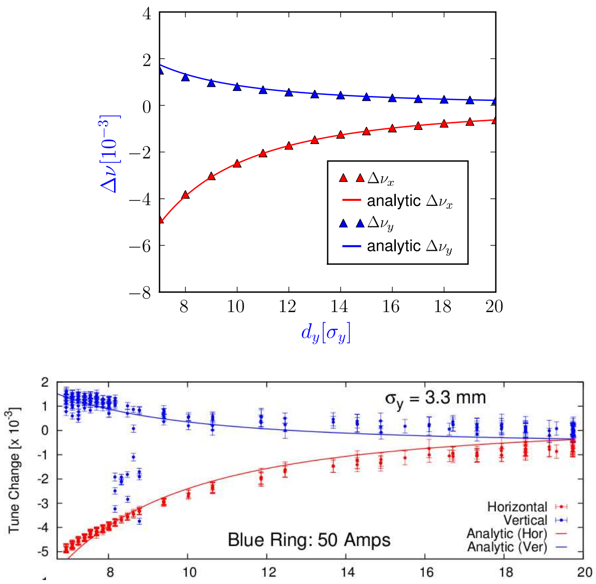

Figure 1: (Color) Plots of tune shift dependence on the wire separation distances: (top) simulation and (bottom) measurement. Solid lines represent the analytic estimation.

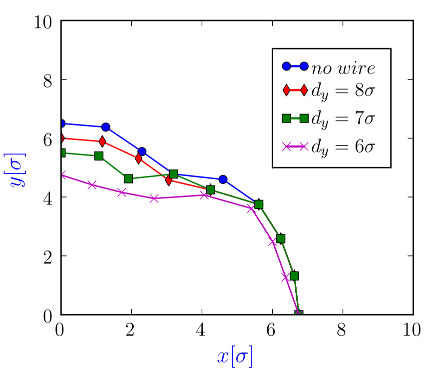

Figure 2: (Color) Plot of dynamic aperture according to wire separation distance at gold-gold collision energy.

experiments are shown in Fig. 1 (bottom), and are also in good agreement with simulation results.

The results of dynamic aperture calculation are shown in Fig. 2. The dynamic aperture of the machine is defined as the largest radial amplitude of particle that survives during the 10^6 turns. In RHIC collision energy optics, the dynamic aperture is limited by IR multipoles, and is ~7σ in average. As in the experiment, the beam-wire separation is entirely in the vertical plane. The dynamic aperture near vertical plane is decreased considerably as the wire approaches to the beam. Its dependence upon the distance d_y at vertical axis is linear. However, the effect of electromagnetic force of the wire is negligible near horizontal plane.

Figure 3 shows the contour plots of dynamic apertures over transverse tunes for three different wire separations. Red indicates low dynamic apertures around 5σ while blue

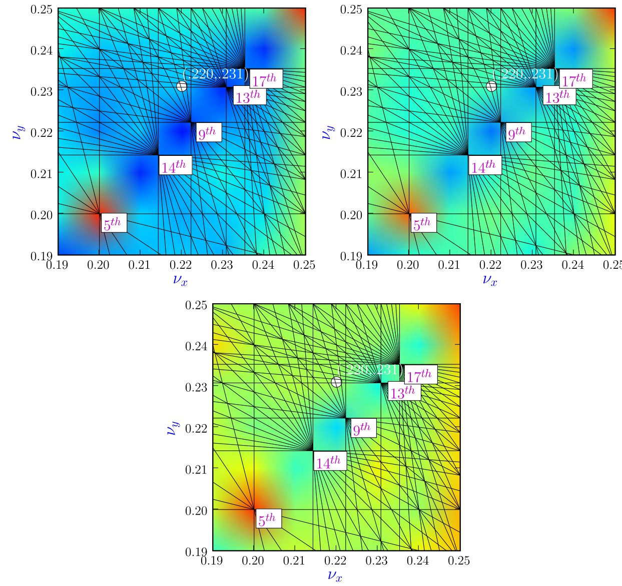

Figure 3: (Color) Tune scan of dynamic aperture at gold-gold collision energy: (top left) $d_y = 8\sigma$, (top right) $d_y = 7\sigma$, and (bottom) $d_y = 6\sigma$. Red and blue colors represent small and large dynamic apertures respectively.

indicates high dynamic apertures around 11σ. In the dynamic aperture calculation, IR multipoles are excluded in order to see the effect of wire alone. The tune scans are performed with increment $\Delta\nu = 0.01$ in transverse directions. As expected, the smallest dynamic aperture is observed near 4^{th} and 5^{th} resonances. It is found that at all wire separations, the largest dynamic apertures are distributed nearly along the diagonal between $\nu_x = 0.21$ and $\nu_x = 0.24$. In the other point of view, the wire kick at a large separation is equivalent to long-range beam-beam interaction. This scan indicates that effects of long-range interactions dominate at off-diagonal region.

Figure 4 shows the simulated diffusion coefficients for gold-gold collision run. The diffusion coefficients can be calculated numerically from $D_{ij} = \langle (J_i(N) - J_i(0)) (J_j(N) - J_j(0)) \rangle / N$, where $J_i(0)$ is initial action, $J_i(N)$ action after N turns, $\langle\rangle$ average over simulation particles, and (i, j) are x or y. The tracking code evaluates the diffusion coefficients in two-dimensional action space with the boundary determined by the dynamic aperture obtained above. The coefficients are averaged at the same action and plotted to compare with the measurements obtained by fitting the time-dependent loss rate after moving the collimator [2]. The vertical axis is a logarithmic scale. It should be noted that dependence of diffusion coefficients on the initial action is exponential. However, since the measured coefficients are fitted by a power law, i.e. $D \sim J^n$, they agreed with simulations only at large actions. Due to measurement limitations, the diffusion coefficients were not measured at small actions. Conversely it is difficult to calculate the coefficients in simulations at large action because some of the particles are lost quickly.

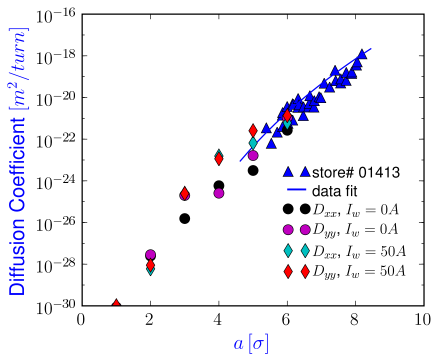

Figure 4: (Color) Plots of diffusion coefficients of gold-gold store of RHIC. The coefficients are calculated in the blue ring. Wire current $I_w = 50A$ and separation $d_y = 8\sigma$ are applied.

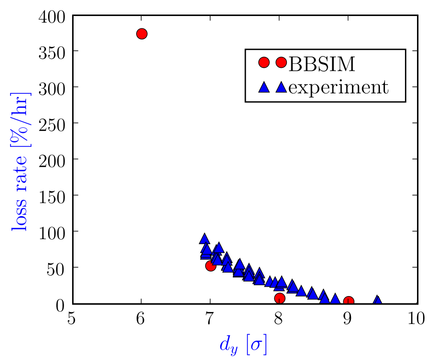

Figure 5: Comparison of the simulated beam loss rates with the measured as a function of separations. Wire current is $I_w = 50A$.

The effects of wire on diffusion coefficients are considerable at large action amplitude, as shown in Fig. 4. For example, the diffusion coefficient at 3σ amplitude becomes 20 times larger when the wire with current $50A$ and separation $d_y = 8\sigma$ is applied.

As mentioned above, the wire affects the beam at large separation like pseudo long-range beam-beam interaction. The wire reduces the dynamic aperture, and increases the diffusion rate. Hence, it is expected that the wire increases beam loss. The beam loss rate due to the wire is shown in Fig. 5. The tracking is done over different wire separations for the wire current $I_w = 50A$. The onset of beam losses is observed at 9σ for both simulation and measurement. As the wire is close to the beam, the beam losses increase. The simulations reproduce well the measured loss rates. Similar good agreement between simulations and measurements for different runs were reported earlier [3, 4].

Figure 6 shows the beam transfer functions for deuteron-gold collision energy and nominal tune $(28.228, 29.225)$. A sinusoidal driving force is introduced into a beam in both horizontal and vertical planes. Because the beam response remembers a driven nonlinear oscillator, it is expected that response curves are different according to the direction of the frequency sweep, i.e., downward or upward. In order to avoid the uncertainty, the relaxation time is applied just before starting BTF evaluation at each successive driving frequency. The response curve reveals two peaks, as shown in Fig. 6 (top). One peak is close to the horizontal tune, and the other is near the vertical one. The wire moves a peak location of tune distribution by 0.003, as shown in Fig. 6 (bottom left), which is consistent with the simulated horizontal beam transfer function in Fig. 6 (bottom right). However, the measured horizontal BTF shows that a peak near horizontal tune is suppressed while the other peak near vertical tune is exaggerated. It is due to the transverse coupling when the wire is present. The coupling effect is also observed in the simulation.

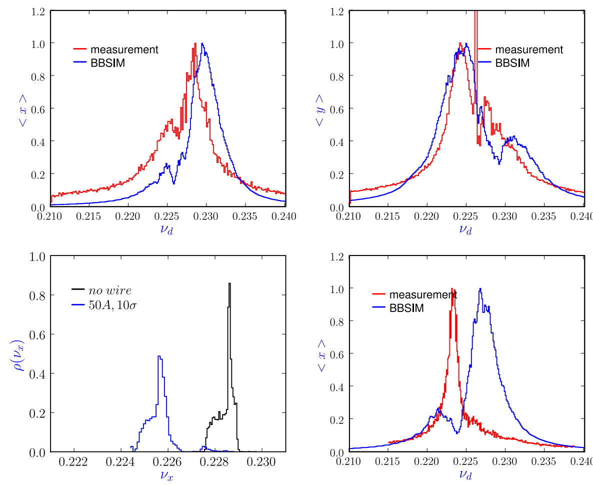

Figure 6: Horizontal (top left) and vertical (top right) beam transfer functions, and (bottom left) horizontal tune distribution and (bottom right) horizontal beam transfer function with wire current $I_w = 50A$ and separation $d_y = 10\sigma$.

SUMMARY

In this paper, we investigated the effect of a current carrying wire on blue beams at collision energy in RHIC using weak-strong simulations. The results show that both simulated and measured tune shifts due to the wire are well agreed with each other. From the tune scan of dynamic aperture, it is shown that the dynamic apertures are dominantly reduced at off-diagonal region due to the wire. The beam loss rate is sensitive to wire separation, and reproducible by the tacking code `bbsimc`.

REFERENCES

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